QUARTERLY REVIEW II

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By Anja Chalmin

The second quarterly review of current developments in geoengineering provides an insight into new geoengineering companies and projects as well as new funding opportunities for geoengineering. The vast majority of new projects and funders are – as before – located in industrialized countries. At the same time, the review reports on delays in the implementation of new geoengineering projects, technical failures and issues with excessive costs, as such problems become known in an increasing number of projects. The review also informs about the growing resistance to current geoengineering proposals. In impacted regions, Indigenous communities, landowners, environmental groups and local governments are speaking out against proposed geoengineering projects because of the associated environmental and health risks.

Enhanced weathering – new investments and increased doubts about its effectiveness using the example of Project Vesta

Enhanced weathering aims to imitate and accelerate the very slow natural weathering and carbonation processes that are estimated to absorb about one billion tonnes of CO_2 from the atmosphere every year. It is a theoretical geoengineering approach that aims to accelerate the carbonation processes by mining, crushing and transporting large quantities of selected rocks, e.g., olivine-rich basalt, silicate rock or wollastonite, and dispersing them onto agricultural land, beaches or

directly into the ocean. The proposal is associated with high energy consumption, mainly due to the increased mining activity and crushing of the rocks, but also because of the transport and distribution of the crushed rocks. Apart from this, there are extensive potential environmental risks. In addition to the damages in the mining areas, there are possible negative effects on marine biochemical processes or the marine food chain. For example, substances can dissolve out of the rocks, "*which could stimulate the growth of certain types of algae and phytoplankton, and otherwise alter ecosystems and food chains in ways that could be difficult to predict*". In terrestrial and marine environments, the release of potentially toxic rock components such as chromium, cadmium and nickel can become a problem. By crushing the rock, such substances can be more easily dissolved and enter environment and food chains.

Many enhanced weathering players have commercial interests. Among them is the San Francisco-based Project Vesta, founded in 2019, whose aim is to test and scale enhanced weathering with olivine – a soft, green volcanic stone – on beaches. Because of its commercial interests, researchers fear that Project Vesta is "*overselling the potential or discounting the difficulties of its approach*". This concerns both the cost and the efficiency of enhanced weathering. Project Vesta meanwhile claims that "*weathering 1 tonne of olivine removes up to 1.25 tonnes of CO_2 from the atmosphere*". However, research shows that the olivine's CO_2 uptake in the ocean could be much lower than assumed by Project Vesta; the uptake capacity measured in the laboratory could be reduced by a factor of five in the ocean due to various chemical interactions. While Project Vesta has overestimated the ability to absorb carbon, they have also greatly underestimated the costs for enhanced weathering: Two years ago, Project Vesta had quoted a cost of US$ 10 per tonne of CO_2 captured. That same year, scientists estimated the costs at between US$ 80 and US$ 180, adding that "*it's cheaper not to emit the stuff in the first place*". Project Vesta presents itself as a public benefit corporation, but registered "Project Vesta" as a protected trademark in the USA in November 2021. Scientists have described Project Vesta as a project that was founded by entrepreneurs and is intended to appeal to entrepreneurs.

After more than two years of preparations without public involvement, Project Vesta has recently made public details of a planned field trial. The trials are to be conducted in two bays near Puerto Plata, in the Dominican Republic. They are likely to be Playa Oscar and Playa Secreta, northwest of Puerto Plata. Project Vesta says it has received approval from the Ministry of the Environment for the first phase of the pilot trial, which includes field testing in so-called mesocosms (large test

tubes in the ocean). The start of the trial is currently announced for 2022; since 2020, the start has already been postponed several times. Details of how much crushed rock is to be spread during the trial and where the rock was sourced are not publicly available.

Project Vesta states that further coastal enhanced weathering trials are planned, "*including locations in the United States, France, in the Caribbean, and India*". At one of the sites, the project has gone past the planning stage. The British Leverhulme Centre for Climate Change Mitigation reports on a collaboration with Project Vesta and in this context mentions a coastal enhanced weathering trial in the USA. In May 2022, a regional newspaper from New York State reported on the planned experiment. Project Vesta has applied to the Town of Southampton on Long Island and to federal authorities for permission to spread olivine on North Sea beach and West Hampton Dunes beach. Since March 2022, Project Vesta has also been looking for a field assistant for a project on Long Island. Dan's Papers strongly questions the project's carbon footprint, inter alia because the crushed olivine to be spread on Long Island beaches is sourced from Norway. In addition, there seems to be a relationship with the Southern California Marine Institute in San Pedro, California in the USA, as Project Vesta is also looking for staff for research activities at this site.

While Project Vesta focuses on coastal enhanced weathering, the Leverhulme Centre for Climate Change Mitigation (LC3M) has been conducting enhanced weathering trials on land since 2016. This involves spreading selected and finely ground rock material onto extensive land areas. The LC3M is leading field trials at agricultural sites in Australia, Malaysian Borneo, the US and the UK. One test site is the Energy Farm, a farm at the University of Illinois Urbana-Champaign. There, the enhanced weathering trials are being carried out on 3.8 ha plots where maize, soybean and miscanthus are grown. In Australia the field trials are being conducted in cooperation with James Cook University on plots of sugarcane in North Queensland. In Malaysia, the enhanced weathering trials are being conducted on the 'Sabahmas Oil Palm Plantation', a farm near Lahad Datu in Sabah managed by the Wilmar Corporation in collaboration with the South East Asia Rainforest Research Partnership (SEARRP).

In 2021, the LC3M received a £ 4.7 million grant from the UK Research and Innovation (UKRI) and the UK Department for Business, Energy and Industrial Strategy (BEIS) and announced further field research into terrestrial enhanced weathering with crushed silicate rock at three sites in the UK, at the Centre for Ecology and Hydrology Plynlimon in mid-Wales, Rothamsted Research grassland experimental platform in

North Wyke, Devon, and Rothamsted Research arable research facility in Harpenden, Hertfordshire. The trials are scheduled to run for 4.5 years.

Oxford University is leading another project on enhanced weathering that is publicly funded. The 'Greenhouse Gas Removal by Enhanced Weathering' (GGREW) project is led by UK researchers but plans to conduct field trials in reef environments in Israel and Australia.

The University of Guelph, Ontario, Canada, and the University of California at Davis, USA, are also conducting publicly funded trials on enhanced weathering. Both projects are working in an agricultural context, with Guelph University investigating wollastonite and UC Davis basaltic rocks. The field trials conducted by the University of Guelph have now been completed and are still being further evaluated.

There are also several new companies whose business model is based on CO_2 capture by enhanced weathering, including the Canadian companies CarbonLock and Planetary Technology and the US companies Eion and Heirloom Carbon Technologies. In March 2022, Heirloom raised US$ 54 million from Carbon Direct Capital Management, Ahren Innovation Capital and Breakthrough Energy Ventures, Microsoft Climate Innovation Fund and additional investors. Heirloom aims to remove one billion tonnes of CO_2 by 2035 – with the current state of research, the company risks generating more CO_2 emissions than it commits to capture, and incurring high environmental costs.

Project Hajar is also based on terrestrial enhanced weathering and aims to mineralise 1,000 tonnes of captured CO_2 annually in peridotite rocks in Oman. In the project, the CO_2 is to be captured from the ambient air beforehand. The project was established by Mission Zero Technologies and Omani company 44.01 in early April 2022. Shortly after, it won a US$ 1 million prize in Elon Musk's XPRIZE Carbon Removal. Mission Zero Technologies is a London-based company and a developer of direct air capture (DAC) technology. 44.01 aims to permanently mineralize CO_2 in peridotite rocks in Oman and has, according to its own statements, developed a technological approach for this: Peridotite reacts with CO_2 and water to form the mineral calcite. In order to accelerate this years-long process, highly carbonated water is to be injected into the rock through targeted boreholes. In March 2022, Shopify announced the purchase of 2,882 tonnes of CO_2 from 44.01. The Oman Drilling Project may have had an influence on the formation of Project Hajar and 44.01. The Oman Drilling Project ran from 2007-2018, was led by Columbia University, USA, and investigated the mineralisation of CO_2 in peridotite rock in the Hajar Mountains in Oman.

44.01 has also entered into a collaboration with the Climeworks AG. Climeworks is a Swiss company that has been developing and marketing DAC technology since 2009. Since 2021, Climeworks and 44.01 have been testing the combination of Climeworks DAC technology with geological CO_2 storage in Oman as part of a joint pilot project. There are no current updates on the progress of the cooperation.

There are no studies on how permanent the mineralisation of CO_2 is in rocks. In real soils, the rate of carbon sequestration can deviate greatly from laboratory conditions. The reason for this is, for example, influences by microbes, which can strongly affect the rate of carbon fixation. Rocks can harbour diverse and active microbial populations. Injection of groundwater enriched with CO_2 can lead to a significant decrease in microbial diversity in rocks and promote the growth of microorganisms, whose activities can prevent mineralisation of CO_2.

The latest player on the topic of enhanced weathering is Travertine Technologies Inc., a University of California spin-off recently founded by Prof. Laura Lammers. The company is based in Boulder, Colorado, and aims to further develop and commercialise an electrochemical process for CO_2 capture. According to Travertine, the process uses sulphate waste from mining and electrical energy, and converts CO_2 into a mineral while producing sulfuric acid. The company is currently looking for partners to scale the technology. In June 2022, the company raised US$ 3 million in funding from the Grantham Foundation and Clean Energy Ventures.

Marine geoengineering – updates on proposals involving marine environments, the Arctic or glaciers

The Arctic Ice Project (AIP) is facing growing opposition from Indigenous communities, environmental and Arctic groups, e.g., because of possible harmful impacts on Arctic fauna, local people and the arctic environment. The Arctic Ice Project suggests covering Arctic land or sea ice with a layer of reflective material to slow down the melting of the ice and/or to restore the ice. The proposed cover substance is a reflective silica glass, consists mostly of silicon dioxide and has the form of tiny hollow glass spheres. In May 2022, researchers from the University of Alaska Fairbanks, USA, described in a publication that surface albedo modification "*are likely to result in unforeseen consequences*" and that such proposals "*have the potential to produce new risks to both natural and human systems*". In May 2022 twelve tribes and more than 25 organisations such as Native Movement and The Alaska Center have spoken out against the Arctic Ice Project. They have signed a letter expressing their worries that the reflective glass spheres could harm animals and people in the Arctic and demanding to cease all

research operations. In May, an Alaska Native delegation attempted to attend an AIP fundraising event in Menlo Park, California, but was not accepted as a participant. The delegation then organised protests outside the event.

The AIP was founded in 2007 by Leslie Field. In March 2022, Leslie Field founded a new company, the Bright Ice Initiative. Her new company intends to test the technology developed at the AIP on sea and glacier ice, for example in Iceland, Canada and Alaska. The company is currently seeking funding to finance future field tests.

Heimdal, a Hawaii-based company, founded by two Oxford University graduates, says it has developed a process to capture CO_2directly from the air using seawater. The process starts by desalinating seawater. Afterwards, the hydrochloric acid is removed from the salt brine through an electrolysis process. The solution is then to be returned to the ocean. Heimdal says by removing the acid, the seawater will on the one hand be neutralised and on the other hand be able to absorb atmospheric carbon. The company plans to sell the hydrochloric acid produced in the electrolysis phase to textile, battery, metal and food manufacturers to reduce the cost of carbon removal, which is around US$ 475 per tonne of captured CO_2. Heimdal's current pilot plant is the size of a shipping container and can capture 36 tonnes of CO_2 per year. Heimdal plans to build a larger pilot plant that can "capture" 5,000 tonnes of CO_2per year. The plant is to be built in Portugal or Dubai.

In June 2022, Chinese researchers of the Chinese Academy of Sciences published results of an experiment in which different textiles were tested to slow down the melting of glaciers. The trial was conducted at Urumqi Glacier No. 1, Tien Shan, China. Three different materials were tested. It is not known how much climate-relevant gases were produced during the manufacture of the respective cover materials. So far, the testing of materials for covering glaciers has mainly focused on glaciers in Switzerland and Austria.

Direct air capture – current information on funding and projects

Although direct air capture (DAC) is one of the geoengineering technologies in which massive public and private investments have been poured for decades, scientists continue to describe DAC as a technology that "*is still in its infancy*". Although there are constantly new technological developments, e.g., in absorbents, the players in the field of DAC have not succeeded in significantly reducing the high costs and immense energy consumption of DAC. Many of the planned DAC projects, for example Haru Oni in Chile or 1PointFive in the USA are delayed,

other projects were cancelled due to high costs, for example Project Dreamcatcher in Scotland. Also, comparing the amount of CO_2 currently captured annually by DAC with current annual emissions of climate gases is devastating after such a long development period and such extensive investments.

There have been a few companies from Europe and the US that have shared the DAC market in the past. Recently, there are several new companies developing and marketing DAC technologies, including Carbon Infinity, Carbon Quest, Noya, RedCarbon, Sustaera and TerraFixing.

Recent developments in Northern America and Europe

Swiss Climeworks AG's 2022 financing round raised around € 585 million from private investors.

In April 2022, Carbyon, a Dutch developer of DAC technology, was awarded US$ 1 million in the XPRIZE carbon removal competition funded by Elon Musk and the Musk Foundation.

In June 2022, New York based DAC technology developer Global Thermostat renewed and extended its joint research and development agreement with ExxonMobil. The agreement aims to scale Global Thermostat's DAC technology.

Global Thermostat's DAC technology will be used in the 'Haru Oni project for the production of Highly Innovative Fuels' (HIF) north of Punta Arenas in the windy province of Magallanes in Chile. HIF, a joint project between AME, Siemens Energy, Porsche AG, ENAP and Enel aims to produce synthetic fuels from captured CO_2, water and energy. The CO_2 is to be captured with wind energy – hence the choice of location. Haru Oni is currently under construction but expected to go into operation in late 2022. In April 2022, HIF secured US$ 260 million in equity investments. HIF plans to use the capital to develop further synthetic fuel projects in the United States, Chile, and Australia, among other regions.

1PointFive, a joint project between Carbon Engineering, Oxy Low Carbon Ventures, a subsidiary of Occidental, and Rusheen Capital, plans to build a commercial DAC plant in the Permian Basin, near an Occidental oil field in Texas. Construction was scheduled to begin in 2021 and has since been pushed back to 2022. Construction is now announced to start in the second half of 2022 and putting the plant into operation has been set for 2024. Although the project has not even started construction, Airbus bought 0.4 million tonnes of CO_2 from

1PointFive in March 2022. The DAC technology for this project is supplied by Carbon Engineering, a company founded by David Keith of Harvard University. For Occidental, this DAC plant is to be the first of many. Occidental Petroleum Corp. announced in March 2022 that it intends to build 70 DAC plants worldwide by 2035, each capturing one million tonnes of CO_2 from the atmosphere annually.

Carbon Engineering also had plans for a joint DAC project with Storegga, considered for the Acorn CCS project at the St Fergus gas plant in Scotland. The so-called Project Dreamcatcher was cancelled in the first quarter of 2022 due to high costs. The available public funding of £ 5 million could only cover about a third of the required costs. Shortly afterwards, in March 2022, Storegga and Mitsui announced joint plans to build a DAC plant at the same site. The proposed DAC plant is expected to capture one million tonnes of CO_2 annually.

Further updates on direct air capture

After many years of developing direct air capture (DAC) technology mainly in Central and Northern Europe and North America, DAC is now also increasingly being developed, researched and marketed in other parts of the world, predominantly in industrialised countries.

In Israel, Amir Shiner, Yehuda Borenstein and Yushan Yan founded the company RepAir Carbon Capture in 2020. RepAir's DAC technology is based on a modular electrochemical approach. CO_2 is captured from ambient air using a membrane and an electrochemical cell. The process requires electrical energy. According to RepAir, the electrochemical cell operates at ambient temperature. How much energy is needed to run the capture process and to release the captured CO_2 from the membrane is not yet publicly disclosed. The energy required to run the plant is to be supplied from renewable energy sources. RepAir is a member of the Brussels-based Negative Emissions Platform, a lobby organization that aims to raise awareness of geoengineering approaches among policymakers and the public.

The High Hopes Labs Ltd is another Israeli DAC developer. The company was founded in 2019 by Nadav Mansdorf and Eran Oren and has already tested its technology in Petah Tikva, east of Tel Aviv, in November 2021. High Hopes Labs is cooperating with its German partner IMPACTECH in Stuttgart. The partners are currently looking for further suitable test sites, e.g., in sub-Saharan Africa. High Hopes' goal is to attach DAC technology to high-altitude balloons and send them to altitudes of about 15 kilometres. At this altitude, the captured CO_2 is to be cooled to -80°C, turned into dry ice ("snow") and to be collected

in a container (the freezing point of CO_2 is -80°C). As it returns to earth, the frozen CO_2 becomes gaseous again and cannot expand due to the closed container – and is supposed to be ready for transport, re-use (CCUS) or for underground "storage" (CCS). By 2024, High Hopes aims to capture one tonne of CO_2 per balloon and per day.

Carbominer, founded in 2020, is registered in Cyprus, headquartered in Ukraine and develops modular DAC systems. Carbominer's DAC technology is based on an ion-exchange sorbent process and an electrochemistry-based regeneration process to release the captured CO_2. Carbominer proposes to install the technology near greenhouses to capture CO_2 on-site and release it in the greenhouses to promote plant growth.

Melbourne-based Southern Green Gas (SGG) started developing DAC technology in 2018 and proposes to use the captured CO_2 as a feedstock for synthetic fuels, fertilisers, to promote plant growth in greenhouses and algae farms, and for carbon capture and storage (CCS). The company's CO_2 capture process is based on a metal-organic framework with nanomaterials and requires electricity that is supplied by solar panels. In June 2022, SGG launched a power-to-X business, converting the captured CO_2 into methanol or kerosene, powered by solar energy.

Membrane-based DAC approaches are being researched at Kyushu University in Fukuoka, Japan.

BECCS – – growing opposition against large-scale projects in the USA and further current developments

The "Midwest Carbon Express", a planned Bioenergy with Carbon Capture and Storage (BECCS) project that aims to connect ethanol refineries across five US states, is facing growing opposition from Indigenous communities, landowners and environmental groups, because of the health and environmental risks associated with CO_2 pipelines and because carbon capture and storage (CCS) has failed to reduce CO_2 emissions. Summit Carbon Solutions, founded by the Summit Agricultural Group, announced the Midwest Carbon Express in 2021, plans to start construction in the second quarter of 2023 and commissioning in the second quarter of 2024. The BECCS project aims to capture, transport and store up to twelve million tonnes of CO_2 annually and plans to capture CO_2 at more than 30 ethanol plants in Iowa, Minnesota, North and South Dakota, and Nebraska. The captured and liquefied CO_2 is to be transported to central North Dakota via pipelines for underground injection. The planned pipeline network is to have a total length of 2,000 miles, of which the largest part, 681 miles, is to be laid in Iowa. In January 2022, Summit Carbon Solutions applied to the responsible authorities for a pipeline

permit for Iowa and in February for South Dakota. In April, the project announced that the first test wells for CO_2 storage had been drilled in North Dakota. Substantial funds are available for the project. By May 2022, Summit Carbon Solutions has raised US$ 1 billion in investment, with major backers including Continental Resources (US$ 250 million), global gas provider technology Xebec Adsorption Inc. (US$ 113.5 million), TPG Rise Climate (US$ 300 million), Tiger Infrastructure Partners (US$ 100 M, April 2022) and South Korean SK Group's energy company SK E&S Co. (US$ 110 million),.

The Midwest Carbon Express is opposed by a diverse group of stakeholders. Where most of the pipeline is located, in Iowa, resistance is strongest. In Iowa, there are a number of activities in which Indigenous communities, landowners, and environmental groups are mobilising against the pipeline. Fifteen counties have raised objections to the pipelines. The Progressive Caucus of the Iowa Democratic Party overwhelmingly passed a resolution in March 2022 opposing the development and construction of the Summit Carbon Solutions pipelines. The resolution was justified as follows: "*The resolution said carbon capture and sequestration is currently unproven technology, asserts increases in jobs will be minimal, and poses safety risks*." The Iowa Utilities Board classified the proposed pipeline as a "*hazardous liquid pipeline*", requiring Summit Carbon Solutions to hold informational meetings in affected counties under Iowa law. But protests and concerns are also being raised in the other US states affected. For example, in North Dakota, the list of counties raising concerns is growing and some counties have passed resolutions against the expropriation of land for the pipeline, and in South Dakota, landowners have joined forces to speak out against the project. In the Iowa permit application, Summit Carbon Solutions has not only requested permission to lay the pipelines, but also permission to expropriate landowners. The company justified the move by saying that not all landowners would voluntarily give up their land for the pipeline. This approach has caused a great deal of resentment, and not only among farmers.

A study conducted by scientists at the University of Wisconsin-Madison proves that the criticism of the project is justified. The study found "*that ethanol is likely at least 24 % more carbon-intensive than gasoline due to emissions resulting from land use changes to grow corn, along with processing and combustion*". A key incentive for the project is the US federal 45Q tax credit, which opens up new revenue streams for power plants and other industrial facilities when CO_2 is captured and used for enhanced oil recovery (EOR) or injected underground. In the US, most of the captured CO_2 in CCS projects is used for EOR – which involves pumping pressurized CO_2 into oil or gas reservoirs to recover

remaining reserves from ageing oil and gas fields and to extract otherwise inaccessible fossil fuels, thereby significantly increasing fossil fuel production. This technology is not new – EOR was developed by the oil industry half a century ago to tap hard-to-reach deep oil reserves. Thanks to the 45Q tax credit, taxpayers are now allowed to help fund such projects that lead to increased production of fossil fuels. CCS is also several decades old, has done far too little since then, but is still presented as a success by its proponents. One example of many is the CCS project at the Terrel gas processing plant in Texas. In its report on the global status of CCS in 2021, the Global CCS Institute describes the Terrel plant's achievement of twenty million tonnes of CO_2 capture, an impressive milestone. The report fails to mention that the Terrel CO_2 capture plant has been in operation since 1972. This corresponds to an annual CO_2 capture volume of 0.4 million tonnes – the same amount of CO_2 that the project had already captured since 1972 and only 80 % of the project's potential maximum capture capacity. Furthermore, the figure of twenty million tonnes of CO_2 does not take into account that the captured CO_2 is used for EOR. When CO_2 is compressed for EOR, about a third of the CO_2 goes straight back into the atmosphere. The fossil fuels extracted by the EOR process generate countless additional emissions, not only when they are combusted, but also during extraction and transport. As the CO_2 capture technology is also very energy-intensive, the project is likely to produce many more emissions than it captures.

In 2021, Navigator CO_2 Ventures, BlackRock Global Energy & Power Infrastructure Fund and Valero Energy Corporation have announced another major BECCS project in the US. The Heartland Greenway project involves the construction of a 1,300 mile pipeline network to pump captured and liquefied CO_2 from up to 30 ethanol or other industrial plants into the Mt. Simon sandstone formation in central Illinois. The project will be carried out in Illinois, Iowa, Minnesota, Nebraska and South Dakota. Each of these ethanol plants will install a CO_2 capture device, liquefy the CO_2, and connect to the main pipeline. So far, only some of the ethanol plants that plan to participate in the project have been made public, including eight Valero plants in Iowa, Minnesota, Nebraska and South Dakota. In March 2022, Siouxland Ethanol LLC, Nebraska, communicated its participation. In May 2022, Big River Resources announced that it plans to participate in the project with three ethanol plants in Iowa and Illinois. In June 2022, POET LLC signed a letter of intent with Navigator CO_2 Ventures to participate in the project and announced plans to capture five million tonnes of CO_2 per year. The number and locations of the ethanol plants with which POET plans to participate in the project have not yet been disclosed. POET LLC is based in Sioux Falls, South Dakota, and is a producer of biomass-based

ethanol. The company owns 33 ethanol plants, most of which use corn for ethanol production and other feedstocks such as agricultural residues, sorghum millet, wheat, barley and potatoes. Several of the ethanol plants already capture CO_2 and sell it to customers in the Midwest for use in food processing, water treatment, fire suppression and agriculture.

Like the Midwest Carbon Express, the Heartland Greenway project is facing growing opposition "from citizens, environmentalists, property rights advocates and landowners in all of the impacted states", for the same reasons as the Midwest Carbon Express.

The issue of safety plays a major role in the discussions about the Heartland Greenway project. The operator describes both the transport routes and the storage as safe. However, this does not correspond to reality, as accidents have already occurred during the transport of CO_2 and the long-term safety of underground storage of CO_2 has not been proven. Illinois activists oppose the pipeline on grounds of safety, environmental impact and land use. The rupture of a CO_2 pipeline in Mississippi in February 2020 is cited as an example of the fears. In the town of Satartia, several hundred people were affected by the CO_2 spill – some suffering from symptoms such as mental fogginess and lung issues for a long time afterwards. Who is responsible if accidents occur during transport or if CO_2 escapes from the planned storage site? Is there an independent audit of the safety of the storage site? On the project website, Navigator CO_2 Ventures states that it intends to carry out regular inspections, for example by weekly helicopter flights. Whether this is an appropriate measure to detect the escape of CO_2 from pipelines and cracks in the subsurface is debatable.

Since 2019, Occidental Petroleum Corporation and White Energy have been planning to establish CO_2 capture plants at White Energy's ethanol plants in Hereford and Plainview, Texas. At both sites, operation of a CO_2 capture plant was scheduled to begin in 2021. The captured CO_2 was to be compressed and used for EOR measures in Occidental Petroleum's oil fields in the Permian Basin. Putting the BECCS projects into operation has been postponed to 2023, the project partners have not published the reason for the delay.

There are also new BECCS projects in the UK and Sweden. The UK projects are both funded by the UK government's Direct Air Capture and Greenhouse Gas Removal innovation programme. InBECCS has been conducting a feasibility study since 2021 for a BECCS project in the north-west of England, to be connected to the existing 28.5 MW biomass gasification plant 'Ince Bio Power Facility' in Protos, Cheshire. A feasibility study

has also been underway since 2021 as part of the KEW Technology project. The project approach combines CO_2 capture and hydrogen production and is to be tested at the KEW Technology gasification plant in Wednesbury near Birmingham, UK.

New BECCS activities were also announced in Sweden in 2021. Biorecro, a Swedish company developing BECCS technology, announced SEK one million in funding from the Swedish Innovation Agency to develop a future BECCS facility at Söderenergis' Igelsta plant. The funding will also be used to develop a method for potential BECCS producers to prove that their process has a net effect of reducing emissions and capturing more carbon than produced in the process. This method will then be tested at Söderenergis' planned future BECCS plant in Igelsta. Igelsta is Sweden's second largest biomass-fired combined power and heating plant, consuming 17,000 tonnes of fuel per week at full capacity (0.88 million tonnes of fuel per year). The project is being carried out by Biorecro, the Research Institute of Sweden, Söderenergi and KLIMPO.

In Japan, Taihei Dengyo Kaisha Ltd. announced plans to build a BECCS plant at its 7 megawatts biomass power plant in Hiroshima Seifu Shinto, an urban complex within Hiroshima City, in late 2021. Mitsubishi Heavy Industries Engineering (MHIENG) was awarded the contract to supply CO_2 capture technology for the proposed project site. The amine-based CO_2 capture technology was jointly developed by MHIENG and Kansai Electric Power Co., Inc. (KEPCO).

BECCS projects are problematic, among other things, because of their large land consumption and are therefore not suitable for large-scale implementation. Scientists describing BECCS, have said that its "*land requirements present a threat to biodiversity*".

CCS – current developments

According to a report produced last autumn by the Global CCS Institute, 27 CCS projects are in operation worldwide and 108 are under development. Some of the current developments will be briefly presented here.

Australia: The commissioning of the Gorgon LNG project was subject to the condition, that the Chevron must capture and inject at least 80 % of the CO_2 emissions released at the site over a five-year period starting in July 2016. In April 2022, the Institute for Energy Economics and Financial Analysis (IEEFA) reports that the Gorgon CCS underperformed its targets by about 50 % and that offsetting this shortfall may cost Gorgon up to AU$ 184 million. Chevron Corp. and its partners in the

Gorgon CCS project have to acquire the offsets by July 2022. The IEEFA states: "*The extent of the technical failure of Gorgon CCS cannot be overstated. It prompts the question: if the engineers from the project backers – the super major oil companies Chevron, Shell and Exxon – cannot get CCS to work as forecast, who can?*"

Australia, Japan: In June 2022, Japanese energy companies JERA, Tokyo Gas and Inpex announced they would join Australia's Bayu Undan CCS project. The companies aim to capture CO_2 in the production of liquefied natural gas (LNG) and hope to transport the captured CO_2 by ship from Japan and inject it underground at the Bayu Undan CCS project. There is talk of investments of up to AU$ 750. The proposed CO_2 injection site for the Bayu Undan CCS project is in the Timor Sea, off the coast of Timor-Leste.

Australia: Santos and new joint venture partner Beach Energy announced the final investment decision for the AU$ 220 million Moomba CCS project. The project is expected to be operational by 2024 and to capture 1.7 million tones of CO_2 per year.

Bahrain: In January 2022, Mitsubishi Heavy Industries EMEA, Ltd, a developer of CO_2 capture technology, and Aluminium Bahrain B.S.C., a major aluminium producer in Bahrain, signed a memorandum of understanding to examine the feasibility of capturing CO_2 from the exhaust gases of an aluminium smelter operated by Alba in Bahrain.

Canada: Shell's Quest CCSProject in Alberta, Canada, was found to be emitting more greenhouse gases than it is capturing. Although the CCS project has captured 5 million tonnes of CO_2 in five years, it has emitted an additional 7.5 million tonnes of climate-damaging gases over the same period, or 1.5 million tonnes annually.

Canada: The SaskPower Boundary Dam project has ongoing technical problems. After the average CO_2 capture rate dropped in recent years, there are new engineering problems. The goal of capturing one million tonnes of CO_2 per year has never been achieved. In 2021 the capture rate was 44 % of the Boundary Dam's emissions – the goal was to capture 90 %.

Canada: "*More than 400 Canadian climate scientists and other academics are pleading with Finance Minister Chrystia Freeland to scrap her plan to create a tax credit for companies that build carbon capture and storage facilities.*"

China: A CCS demonstration project planned by Huazhong University of Science and Technology in Yingcheng for Jiuda Salt's power plant in

Yingcheng city was suspended in March 2022. No reason was given for the abandonment of the project.

Denmark/Germany: The Greensand CCS Project aims to store captured CO_2 in the Danish part of the North Sea, in the Siri field, which is located about 200 km west of the Danish coast. In the German state of Schleswig-Holstein, which lies south of Denmark, the state government has expressed criticism on Denmark's plans for a CO_2 storage site in the North Sea: "*If CO_2 is now to be stored underground in a pilot project off the Danish coast, then it must be absolutely ensured that this procedure has no impact on humans, nature and the environment*," said Environment Minister Jan Philipp Albrecht (Greens). In Schleswig-Holstein, underground storage of CO_2, including the coastal areas, is prohibited by law.

Egypt/Italy: Egypt and Italy's Eni announced plans for a joint CCS project, capturing up to 0.03 million tonnes of CO_2 per year. The captured CO_2 is to be stored in the Meleiha field.

India: In April 2022, the Indian Koyali refinery CCS project signed a memorandum of understanding with Norway's Equinor ASA for cooperation.

Norway: In 2022, the EU has designated Northern Lights as a Project of Common Interest and awarded € 4 million under the Connecting Europe Facility funding scheme. In May 2022, Cory and Northern Lights signed a memorandum of understanding and plan to explore the opportunity to ship carbon from Cory's energy from waste operations on the River Thames in London to Northern Lights' subsea carbon storage facilities in Norway.

Qatar: In June 2022, Total Energies joined the North Field East CCS project in Qatar.

Russia: A proposed CCS project at the Novatek Yamal LNG plant in Sabetta, Yamal Peninsula, Russia, is currently awaiting a final investment decision. A pre-FEED study was completed in February 2022.